

GEORGIA INSTITUTE OF TECHNOLOGY

ATLANTA, GEORGIA 30332

ENGINEERING COLLEGE
OFFICE OF THE DEAN

February 29, 1968

ANNUAL REPORT: NSF Grant No. GK 135, "Transient Free Convection in a Closed Container with Heating at the Bottom and at the Sides," initiated January 1, 1965 and extended without additional funding through June 30, 1968.

PRINCIPAL
INVESTIGATOR: Dr. Walter O. Carlson
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

SUMMARY:

An understanding of the phenomena associated with turbulent, free convection in closed containers and the ability to predict these phenomena is of considerable interest in a number of engineering applications. Considerable progress has been made on this problem in recent years both by the investigators under this grant and others as well. When large volumes of fluids are subjected to heat transfer from the surroundings, the energy transferred to the fluid is concentrated in the upper portion of the fluid. This phenomenon is called thermal stratification. In many applications it is not desirable to have stratification occur and some means of alleviating this situation must be devised.



SUMMARY (Cont'd):

There are basically two methods of reducing stratification: (1) Mechanically, for example the use of pumps, and (2) Passively, for example changing the container geometry and/or adding baffles to the container walls. Under the present grant passive remedies for the stratification problem are being investigated. A study of the use of baffles is now in its final phases and considerable experimental data have been collected to date. Preparations for experimental studies of the effects of bottom shape are now under way.

During the reporting period a master's thesis was completed on measurement errors in the system being used for the testing. Modifications of the equipment were also made for the baffle studies and various baffle arrangements were designed and constructed.

DISCUSSION:

The research conducted during this reporting period consisted of: (1) Error analyses of the experimental techniques and assumptions used in the experiments. (2) Modifications to existing equipment and development of instrumentation for baffle studies. (3) Data collection and preliminary results of baffle studies.

DISCUSSION (Cont'd):

1. Errors in Experimental Measurements -

In this phase of the experimental program it was found that the bulk temperature probe did not affect the temperature readings. Tests were conducted using probes of various diameters in the small tank. Photographic analysis of the particle motion in the small tank revealed that the assumption of two-dimensional flow is valid after only a short initial transient start-up time. It should be noted that the convective flow in the small tank is laminar.

In the large tank the convective flow is mainly turbulent. Particle photographs taken in a horizontal plane revealed that the flow is not two-dimensional and that large vortices exist in this plane. Therefore, a three-dimensional vortex system exists in the tank. Photographs previously taken in a vertical plane had shown the existence of vortices in that plane.

2. Modifications to Test Tank and Instrumentation for Baffle Studies -

The large tank and instrumentation used by Tatom in

DISCUSSION (Cont'd):

2. Modifications to Test Tank and Instrumentation for
Baffle Studies (Cont'd) -

the first phase of these studies* has been modified for the baffle studies. A control panel was built from which complete remote operation of the test tank is possible. Thermocouples were added on the back side of the vertical heating panels so that the wall temperature distributions could be determined. A photograph of the large test tank and control panel are shown in Figure 1.

The range of parameters for the baffle tests have been selected as follows:

- a. Water depth - to - tank width ratios of 1, 3, and 4.88.
- b. Bottom-to-side wall heat flux ratios of 0, 0.48, 1.51, 4.0, and 8.09.
- c. Baffle widths of 2, 4, and 6 inches at angles of 45° , 90° , and 135° from the vertical.

* Annual Report on NSF Grant No. GK 135, dated March 22, 1967 and Ph.D. thesis by J. W. Tatom, "Transient Free Convection in a Closed Container with Heating at the Bottom and at the Sides," School of Mechanical Engineering, Georgia Institute of Technology, May 1966.

DISCUSSION (Cont'd):

2. Modifications to Test Tank and Instrumentation for
Baffle Studies (Cont'd) -

- d. Gr^* values from 1.01×10^{11} to 5.33×10^{14} .
- e. Bottom heating rates from 0 to $1.87 \text{ BTU/sec-ft}^2$.
- f. Side wall heating rates from 0 to $0.121 \text{ BTU/sec-ft}^2$.
- g. Test times to 3600 sec.

3. Preliminary Results of Baffle Studies -

The bulk temperature profiles with baffles in the tank are being compared to the temperature profiles under the same test conditions without baffles. Some of the preliminary results indicated that some baffle designs are not too effective in reducing stratification. This is particularly true in the higher heat flux cases. At low heat fluxes some of the baffle designs are proving to be effective in promoting mixing of the fluid. The apparent reason for the baffles not being effective at the higher heat fluxes is that the fluid in the top two feet of the tank is considerably warmer than in the

DISCUSSION (Cont'd):

3. Preliminary Results of Baffle Studies (Cont'd) -

lower portions of the fluid. Therefore, the baffles appear to be more effective in the lower strats of the tank.

The addition of baffles on the vertical walls of the tank create a mixing which, in some cases, extends into the bulk and in other cases it does not. Figures 2 and 3 show qualitatively the mixing action when three six inch baffles are added on each wall at an angle of 45° . The particle streaks in the photographs illustrate the fluid velocity indirection. The photographs shown are for the middle baffle which is located in the middle of the tank wall. Although there is more mixing action at later times, as shown in Figure 3, the baffle effectiveness decreases because of the large fluid surface temperatures experienced at later times.

To date, approximately fifty tests have been made with baffles and the data are being reduced, plotted and correlated. The wall temperature measurements are also

DISCUSSION (Cont'd):

3. Preliminary Results of Baffle Studies (Cont'd) -
being correlated with the analytical results of the previous phase of this investigation. It is anticipated that these measurements will yield Nusselt number correlations for convection in closed containers. Very little information exists on heat transfer correlations for the film coefficients for free convection for these configurations. In addition, the information that is available is only for the case of laminar flow along the walls, while the present research will provide values for turbulent flow.

GRANT ACTIVITIES:

1. Publications:

Schneider, Edward H., "Errors in Experimental Measurements in Free Convection of Fluids in Closed Containers", M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, August 1967.

2. Students and Professional Staff:

a. Supported by Grant -

(1) Dr. Walter O. Carlson, Professor

GRANT ACTIVITIES (Cont'd):

2. Students and Professional Staff (Cont'd):

- (2) Mr. Reginald B. Pollard, Ph.D. student
- (3) Mr. Edward H. Schneider, M. S. student
- (4) Mr. Rodney L. Tennyson, Undergraduate student

b. Other Support -

- (1) Mr. Wallace W. Carr, Ph.D. student



Legend:	A - Light Source	E - Potentiometer
	B - Thermocouple Junction Box	F - Ampere Meter
	C - Camera and Tripod	G - Side Voltmeter
	D - Tape Recorder	H - Bottom Voltmeter

Figure 1. Experimental Apparatus

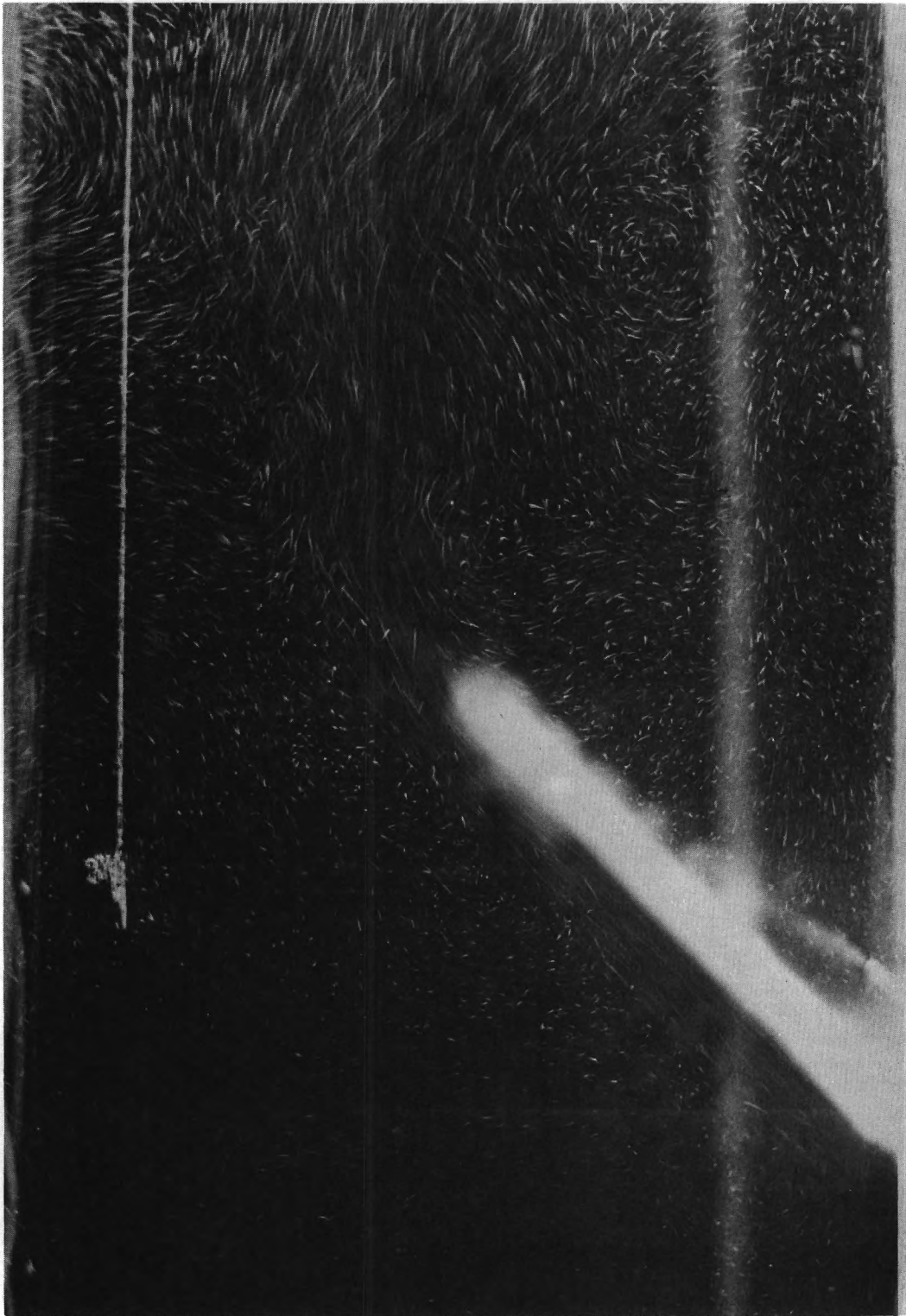


Figure 2. Flow around a 6 inch Baffle after 2 seconds;
 $\theta = 45^\circ$, $Q_B/Q_S = 0.45$.

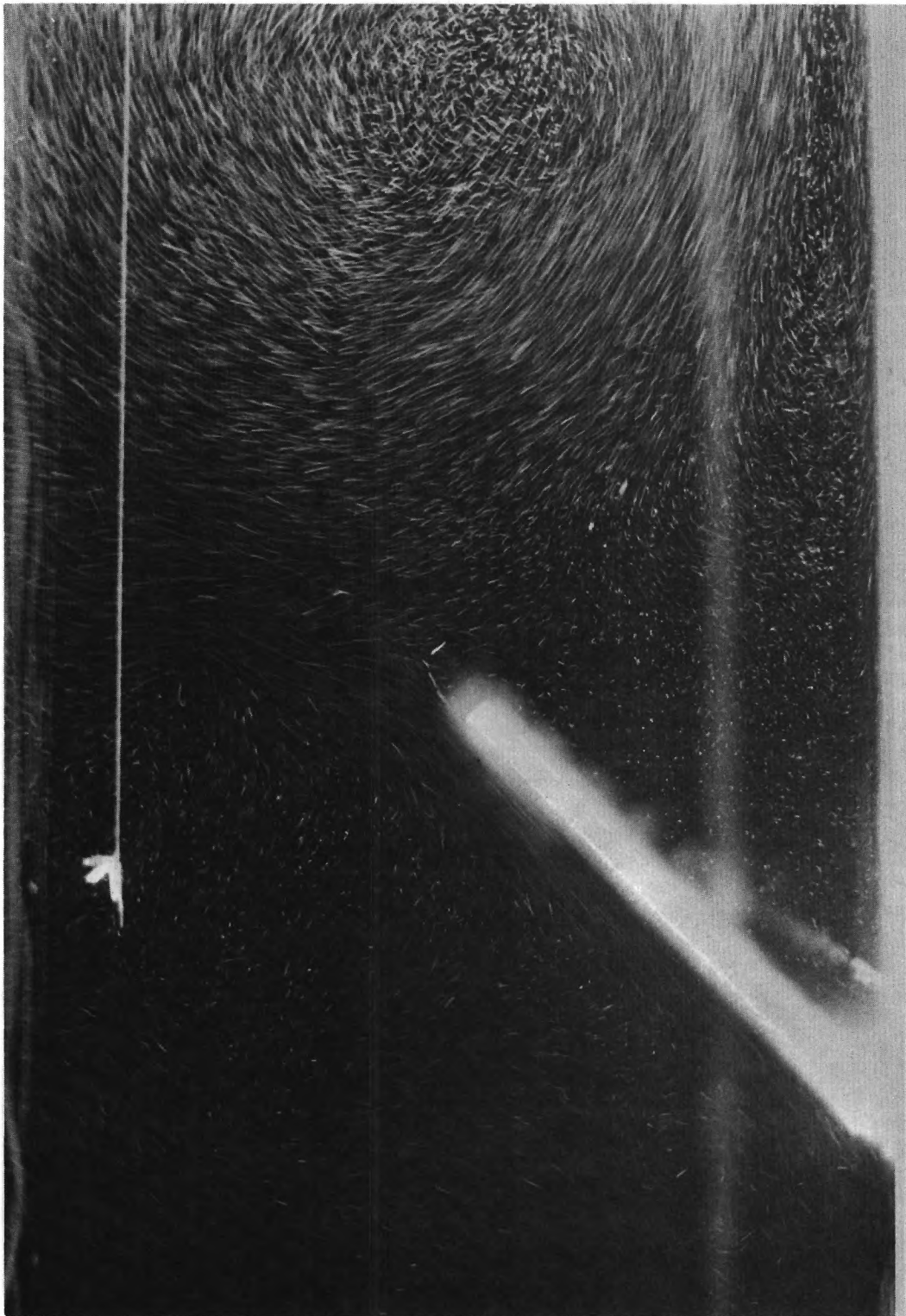


Figure 3. Flow around a 6 inch Baffle after 20 seconds;
 $\theta = 45^\circ$, $Q_B/Q_S = 0.45$.

ERRORS IN EXPERIMENTAL MEASUREMENTS IN FREE
CONVECTION OF FLUIDS IN CLOSED CONTAINERS

A THESIS

Presented to

The Faculty of the Graduate Division

by

Edward H. Schneider

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Mechanical Engineering

Georgia Institute of Technology

August, 1967

SUMMARY

In the present series of experimental investigations of transient free convection of water in enclosed containers there are at least two possible areas of concern which may lead to erroneous results and conclusions. These two areas are the effects of thermocouple probe diameters on the recorded temperatures and the possible existence of three-dimensional flow. A two foot square tank with a height of three feet was used in the tests. Two opposite sides and the bottom were heating plates and the other two sides were glass.

Tests were conducted under conditions of laminar free convection through the use of four different probe diameters varying from a single thermocouple to a probe six inches in diameter under the same heat transfer conditions. These tests showed that there was no significant effect of probe diameter on the bulk temperature readings. Calculations, verified by measurement, also showed there were no effects due to orientation of the thermocouples.

Photographic and visual studies taken in the horizontal plane in the laminar free convection region showed that the assumption of no motion in this plane is true shortly after heating was initiated. In the turbulent free convection region, using a 10 ft. tank, a vortex motion was observed in the horizontal plane, in addition to the previously observed vortex motion in the vertical plane at the outer edge of the turbulent boundary layer throughout the entire test period.

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

January 6, 1969

Dr. Royal E. Rostenbach
Acting Program Director
Engineering Energetics
Engineering Division
National Science Foundation
Washington, D.C. 20550



Dear Dr. Rostenbach:

Enclosed you will find the final report on N.S.F. Grant No. GK 135, "Transient Free Convection in a Closed Container with Heating at the Bottom and at the Sides." Also enclosed you will find four copies of a paper which has been accepted for publication in the Eckert Anniversary Volume, Progress in Heat Transfer, 1969.

I wish to express my gratitude to the National Science Foundation for the support granted for this research. In addition to myself, six students have been supported under the grant and three others have participated in the program. The facilities developed under the grant will be used for further experimental studies in free convection.

Sincerely yours,

Walter O. Carlson
Associate Dean and
Professor of Mechanical
Engineering

WOC:gp

cc: Dr. S. P. Kezios
Mr. H. L. Baker, Jr.

Handwritten: HLR 1/7/69

Final Report: NSF Grant No. GK 135, "Transient Free Convection in a Closed Container with Heating at the Bottom and at the Sides," initiated January 1, 1965 and extended without additional funding through June 30, 1968.

Principal Investigator: Dr. Walter O. Carlson
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

SUMMARY:

In a number of engineering applications there is a need for a better understanding of transient free convection phenomena in vertical, finite closed containers where the fluid is heated both at the bottom and the sides without change of phase of the fluid and where a large percentage of the energy transfer to and within the fluid system occurs under turbulent conditions. Considerable progress has been made on this problem in recent years both by the investigators under this grant and others as well. When large volumes of fluids are subjected to heat transfer from the surroundings, the energy transferred to the fluid is concentrated in the upper portion of the fluid. This phenomenon is called thermal stratification. In many applications it is not desirable to have stratification occur and some means of alleviating this situation must be devised.

Experimental studies of transient, turbulent free convection were conducted in a closed test tank with heating at the bottom and sides with water as the test fluid. Two phases of the stratification problem were investigated under this grant. In the first,

the test tank and required instrumentation were designed and built and axial temperature and velocity measurements were made at various aspect ratios, $Gr^* = g\beta q x^4 / k v^2$ and bottom-to-side heat flux ratios. The second phase involved a study of the effects of baffles on the reduction of stratification. Sidewall baffles of various configurations were investigated under the test conditions used for the first-phase investigation.

Under this grant one PhD thesis, two MS theses and one paper have been published. A second PhD thesis is now being written and a second paper has been accepted for publication. Preprints of the second paper are enclosed and the PhD thesis will be forwarded when completed. A third paper has been completed and will be submitted for publication. A complete list of publications is given at the end of this report.

DISCUSSION:

The main piece of test equipment for this research was a test tank having a height of 117 inches with two opposite sides and the bottom heating surfaces, made of 0.025 Inconel sheet backed with a 2-inch layer of Foamglass insulation. The sides were 24.5 inches apart, provided with buss bars at several locations along their height for connection to an electric power source. The other two sides of the tank were glass panels to permit visual, photographic and Schlieren observations of the fluid motion.

Vertical center-line temperature profiles as a function of time were measured for all tests, with and without baffles, with a thermocouple probe constructed of 2-inch diameter plexiglass tubing 119 inches long. The probe contained 59 calibrated twenty-gage copper-constantan thermocouples coated with water-proof polyvinyl plastic. Tests were constructed to determine the effect of probe diameter and orientation on thermocouple readings (4)*. Four different probe diameters varying from a single thermocouple to a probe six inches in diameter under the same heat transfer conditions were used for the tests. The tests showed that there was no significant effect of probe diameter on the bulk temperature readings. Calculations, verified by measurement, also showed there were no effects due to orientation of the thermocouples.

An optical-photographic technique was developed to obtain both quantitative and qualitative velocity data on the convective flow in the tank (1). The quantitative data were obtained by the use of a photographic technique where illuminated, neutral-density 0.002-inch diameter hollow glass Eccospheres were suspended in the water. Qualitative fluid flow information was also obtained using a Schlieren system.

* Numbers in parentheses refer to Publications listed at the end of this report.

During the first phase of the experimental program, convective flow in the tank without baffles was investigated (2,3).

A series of thirty tests were analyzed where data had been collected over a range of test parameters in the vertical tank for sidewall heating only, bottom heating only, and combined sidewall and bottom heating. The range of test parameters was as follows:

- Water depth-to-tank width ratios of 1, 3, and 4.88.
- Ratios of bottom-to-sidewall heating from 0 to 9.4.
- Gr^* maximum values from 1.32×10^{11} to 5.28×10^{14} .
- Test time from 1800 to 7200 seconds.
- Maximum temperature rise in tank from 2.4 to 14.8° F.
- Bottom heating rates from 0 to 0.1933 BTU/sec-ft².
- Sidewall heating rates from 0.0147 to 0.171 BTU/sec-ft².

The temperature profile data were correlated with expanded and improved versions of an analysis previously developed by Tatom for the cases of side heating only and combined side and bottom heating. For the combined side and bottom heating, the correlation of the data shows that the analysis adequately predicts the liquid thermal behavior for most engineering purposes. In the lower regions of the tank, however, there are some improvements which could be made to give better predictions. The basis for a more precise analysis would be that it was found that the temperature profiles were similar. With side heating only, only limited success of correlation was obtained for large Gr^* . On the basis of the experimental results, it is suggested that substantial improvement could be made by incorporating the concept of heat diffusion across the turbulent boundary layer

into the analytical model.

It was found that the characteristic S-shaped temperature profiles at large Gr^* is caused by eddy diffusion of heat across the boundary layer directly to the bulk liquid once the flow becomes turbulent. While a portion of the sidewall heat is carried away by the boundary layer and ultimately near the surface is transported out into the thermal layer, a significant percentage of the heat never reaches the surface, but is absorbed directly by the liquid. In the situation with combined heating, the bottom heat addition produces a fairly uniform temperature in the lower regions of the tank due to turbulent mixing in the vertical direction.

It has been assumed that the width of the tank between the two glass surfaces was sufficient so that when measurements were made in the region midway between the surfaces, no boundary layer effects from these surfaces would exist. Photographic and visual studies in the horizontal plane in the laminar free convection region showed that the assumption of no motion in this plane is true shortly after heating was initiated (4). In the turbulent free convection region, using a 10-foot tank, a vortex motion was observed in the horizontal plane. This motion exists in addition to the previously observed vortex motion in the vertical plane at the outer edge of the turbulent boundary layer throughout the entire test period.

-6-

In many applications it is not desirable to have stratification occur and some means of alleviating this situation must be devised. There are basically two methods of reducing stratification: (1) Mechanically, for example, using pumps, and (2) Passively, for example, by changing the container geometry and/or the addition of baffles to the container walls. Under this grant the use of baffles was investigated in the second phase of the experimental program (5,6).

Approximately fifty tests were made with baffles. The range of test parameters for these tests was as follows:

- Water depth-to-tank width ratios of 1, 3, and 4.88.
- Bottom-to-sidewall heat flux ratios of 0, 0.48, 1.51, 4.0 and 8.09.
- Baffle widths of 2, 4, and 6 inches at angles of 45°, 90° and 135° from the vertical.
- Gr* values from 1.01×10^{11} to 5.33×10^{14} .
- Bottom heating rates from 0 to 1.87 BTU/sec-ft².
- Sidewall heating rates from 0 to 0.121 BTU/sec-ft².
- Test times to 3600 seconds.

Bulk temperature profiles with baffles in the tank were compared to the temperature profiles under the same test conditions without baffles. Comparisons were made on the basis of a baffle effectiveness derived by Vliet*. A number of interest-

* Vliet, G. C. and Grogan, J. J., "Experimental Investigation of the Effects of Baffles on Natural Convection Flow and Stratification," Proceeding of the Conference on Propellant Tank Pressurization and Stratification, Vol. II, NASA, Huntsville, Alabama, January, 1965.

ing and important results were obtained from these investigations.

For a given number of baffles, it was found that there is an optimum size for each aspect ratio and that the optimum baffle size decreases with aspect ratio. For a given baffle size, there is an optimum number of baffles for maximum effectiveness. The number of baffles needed depends not only on the aspect ratio, but on the baffle-to-tank width ratio and heat flux ratio. Further, if the distance between successive baffles is considerably reduced, separation of the boundary layer flow will not occur and the effectiveness is decreased.

Horizontal baffles were found to be generally more effective than baffles concave up or down. The degree of stratification also depends on the heat flux ratio, decreasing as this ratio increases to values near one. For much larger values of bottom-to-sidewall heating ratios, the effectiveness is decreased. Higher effectiveness values were obtained in this investigation than previously reported. This is due to the increased bulk mixing produced by the baffles. Instead of the wall heated fluid reattaching to the back side of the baffles with increasing time, as previously reported, the flow generally separated from the baffles. The effectiveness values decrease with increasing baffles. The effectiveness values decrease with increasing time, approaching asymptotic values. It was found that the system can be assumed to be in a quasi-steady state after the first five

minutes of heating. The approach to quasi-steady state is a function of the heat flux magnitude and container size. Heat transfer measurements were also made on the vertical walls of the container. It was found that local Nusselt numbers in the turbulent regime were slightly higher than those predicted by theory for a vertical surface in an infinite medium.

Further correlations of the data on the effect of baffles are being made and should be completed in the near future. The final results will be given in publication 6. The important results of the investigation have been summarized above. Reference is made to the listed publications for more detailed information.

PUBLICATIONS:

1. Richard V. Brooks, "Free Convection Velocity Measurements by the Use of Neutral Density Particles," M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, June, 1965.
2. John W. Tatom, "Transient Free Convection in a Closed Container with Heating at the Bottom and at the Sides," PhD Thesis, School of Mechanical Engineering, Georgia Institute of Technology, May, 1966.
3. J. W. Tatom and W. O. Carlson, "Transient Turbulent Free Convection in Closed Containers," Proc. of the Third Int. Heat Transfer Conf., August 7-12, 1966, Chicago, Illinois, Vol. II, p. 163.
4. Schneider, Edward H., "Errors in Experimental Measurements in Free Convection of Fluids in Closed Containers," M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, August, 1967.
5. R. B. Pollard and W. O. Carlson, "An Experimental Investigation of the Effect of Baffles on Transient Natural Convection of a Confined Fluid," accepted for publication in the Eckert Anniversary Volume, Progress in Heat Transfer, 1969.
6. R. B. Pollard, "Experimental Investigation of the Effect of Baffles on Natural Convection of a Confined Fluid," PhD Thesis, School of Mechanical Engineering, Georgia Institute of Technology, to be published, 1969.
7. R. B. Pollard and W. O. Carlson, "Turbulent Free Convection Over a Vertical Plate with Uniform Heat Flux," to be submitted for publication.

Copies of publications 1-4 have been previously submitted to the National Science Foundation; copies of publication 5 are enclosed with this report; copies of publication 6 will be forwarded when completed; and copies of publication 7 will be forwarded if accepted for publication.

STUDENTS AND PROFESSIONAL STAFF PARTICIPATING IN PROJECT:

A. Supported by grant.

- (1) Walter O. Carlson, Professor.
- (2) Reginal B. Pollard, PhD Student.
- (3) Ronald D. Ballard, M.S. Student.
- (4) Richard V. Brooks, M.S. Student.
- (5) Edward H. Schneider, M.S. Student.
- (6) Michael Yaksh, Undergraduate Student.
- (7) Rodney L. Tennyson, Undergraduate Student.

B. Other support.

- (1) John W. Tatom, PhD Student.
- (2) Wallace W. Carr, PhD Student.
- (3) Albert W. Forrest, M.S. Student.